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Rugby hohlraum campaign on the National Ignition Facility: status and comparison with modeling

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Abstract. Rugby-shaped gold hohlraums driven by low-adiabat laser pulse shapes have begun to be tested on the National Ignition Facility (NIF). The rugby hohlraum affords a higher coupling efficiency than a comparably sized cylinder hohlraum or, alternatively, improved drive symmetry and laser beam clearances for a larger hohlraum with similar cylinder wall area and laser energy. An inaugural (large rugby hohlraum) shot at low energy (0.75 MJ) to test laser backscatter resulted in a moderately oblate CH capsule implosion, followed by a full energy shot (1.3 MJ) that gave a highly oblate compressed core according to both time-integrated and –resolved x-ray images. These two implosions utilized reduced wavelength separation (1.0 Å) between the outer and inner cones to provide an alternative platform free of significant crossed beam energy transfer for simplified hohlraum dynamics. Post-shot radiation-hydrodynamic simulations in 2- and 3-D, however, show mildly prolate or nearly round implosions, in striking contrast with observations. An analytic assessment of Rayleigh-Taylor hydrodynamic instability growth on the gold-helium gas-fill interface shows a high potential for significant linear growth, saturation and transition to a highly nonlinear state. The presumed seed for instability growth is laser speckle during the early-time laser picket episode in the presence of only partial temporal beam smoothing (1-D SSD and polarization smoothing). Radiation-hydrodynamic 2-D simulations adapted to include a dynamic fall-line mix model across the unstable Au-He interface show good agreement with the observed implosion symmetry for both shots for an interface-to-fall-line penetration fraction of 100%. Physically, the mix layer in a rugby hohlraum acts as an enhanced wall motion to thwart inner-beam propagation, due largely to the confluence of rugby shape and inner-beam propagation angles to the hohlraum symmetry axis. Remedial measures to offset the potential effects of mix in rugby-shaped hohlraums are proposed.

1. Introduction

Interest in testing rugby-shaped hohlraums on the NIF is based on a legacy of successful campaigns at the Omega laser facility [1], using both vacuum [2] and gas-filled hohlraums [3]. For gas-filled rugby hohlraums driven by ignition-like, high-contrast laser power histories, the measured peak drive temperatures were nearly10% higher than in cylinders, the laser-plasma mediated backscatter was low (~1%), capsule implosion symmetry was acceptable, and the number of DD neutrons handily established a record ($>10^{10}$) for indirect drive at Omega. For these reasons, a campaign has begun on the NIF to assess the potential advantages of a rugby-shaped hohlraum at ignition scale.

The benefits of a rugby-shaped hohlraum over a conventional cylinder [4] can be exercised in two ways. First, one can maintain the same radius as a cylinder to take advantage of the nearly 30% reduction in surface energy and achieve a nearly 20% improvement in peak drive x-ray flux. On the other hand, one can use a rugby with similar surface area to a cylinder to achieve a similar drive but with improved beam clearances (to the capsule and laser entrance holes) and higher hohlraum case-to-capsule ratio (CCR) for greater smoothing of hohlraum radiation modes. The strategy chosen for initial testing of the rugby hohlraum on the NIF was to field a 7.0 mm diameter ("700") rugby that has ~8% more surface area than the standard 5.75 mm ("575") cylinder hohlraum [5] in order to define a novel platform that does not require the need for wavelength separation between the outer and inner laser beams for robust inner beam propagation and effective symmetry control.

2. Experimental Results

The first shot (N130318) was conducted at nearly half energy (0.75 MJ, 300 TW for 1.335 ns) in order to guard against unexpected high backscatter and increased risk to the laser optics. The second shot (N130502) was performed at full energy (1.32 MJ, 370 TW for 2.6 ns). Both shots used a 700 rugby hohlraum with 10.5 mm length, a laser-entrance-hole (LEH) fraction of 50.6%, a pure helium gas fill density of 1.2 mg/cc, and a nominal "Symcap" CH ablator with buried ("1x") silicon-doped layers [6]. The rugby shape was prescribed as an offset circular arc of rotation around the symmetry axis [7]. Both shots employed a low-foot, low-adiabat pulse shape, which at full energy is ~20 ns in duration. A mild wavelength separation of 1.0 Å between the outer (44.5°, 50°) and inner (23.5°, 30°) cones was employed. A pair of static x-ray imagers (SXI) viewing through the two LEHs at 18° and 19° to the hohlraum axis provided time-integrated information on wall motion and laser spots.

2.1. N130318 shot summary

This exploratory first rugby shot used a ^{4}He-filled Symcap capsule for core self-emission imaging. Table 1 shows the degree of time-integrated core distortion (3-5 keV), which is significantly oblate ($a_2/a_0 \sim$ -32%). The x-ray bang time of the implosion as inferred from the gated x-ray detector (GXD) was ≥22.9 ps, and the Dante-inferred peak temperature was ~260 eV. A gold M-band fraction for energies above 1.8 keV was ~13%, according to Dante. The total backscatter energy (~41 kJ) fraction was only 6%, residing almost entirely in SRS from the inner cones and only a small amount (<3 kJ) in SBS. The degree of hot electron generation as deduced by the FFLEX diagnostic was low, corresponding to hard x-ray production less than 5 KJ (over the range 20-80 kJ) with harder x rays above 170 keV amounting to less than 1 kJ. In summary, the coupling efficiency of laser energy to x-ray drive energy was high (~94%), but the marginal implosion symmetry suggests that the inner beam propagation to the hohlraum equator was impeded more than pre-shot simulations had predicted. The SXI results were inconclusive in constraining the degree of inner-beam propagation.

2.2. N130502 shot summary

This nominal full energy rugby shot used a ^{4}He-D filled Symcap capsule for core self-emission imaging and neutron data generation. Table 1 shows the degree of time-integrated core image (3-5 keV) distortion, which is severely oblate ($a_2/a_0 \sim$ -71%). The time of peak x-ray emission of the implosion was 21.4±0.08 ns according to the GXD [and 22.2 ns from the Streaked Polar Instrument for Diagnosing Energetic Radiation (SPIDER) diagnostic], and the Dante peak temperature was ~292 eV with a gold M-band fraction of only 11%. The total backscatter energy (~90 kJ) was only 7% of the incident laser energy, comprised almost entirely of SRS from the inner cones and only a small amount (<5 kJ) in SBS. The DD neutron yield was $1.8\text{x}10^{11}$, and the peak deuterium ion temperature from the Neutron Time Of Flight (NTOF) diagnostic was 2.1 keV. The degree of hot electron generation as deduced by the FFLEX diagnostic was again low, corresponding to a hard- x-ray production less than 30 KJ (over the range 20-80 kJ), with harder x rays above 170 keV less than 0.6 kJ. The significantly reduced FFLEX x-ray signal compared with comparable cylinder hohlraums is

Shot number	a_0 [μm] (obs.)	a_2 [μm] (obs.)	a_4 [μm] (obs.)	a_0 [μm] (η_p=0)	a_2 [μm] (η_p=0)	a_4 [μm] (η_p=0)	a_0 [μm] (η_p=1)	a_2 [μm] (η_p=1)	a_4 [μm] (η_p=1)
N130318	50	-16	7	57	+9	+0	51	-12	6
N130502	49	-35	19	61	+3	-2	53	-26	8

Table 1. Observed (shaded) and simulated Legendre moments a_n of 17% time-integrated fuel self-emission contours with fall-line penetration fraction η_p.

likely due to the reduced SRS resulting from the low wavelength separation (1.0 Å) used. In summary, the coupling efficiency of laser energy to x-ray drive energy was high (~93%), but the poor implosion symmetry indicates that the inner beam propagation to the hohlraum equator was severely impeded. The high coupling efficiency is largely an artifact of the reduced inner beam intensity from the low wavelength separation used, and the attendant relatively low values of SRS.

3. Simulation Results

By far the greatest anomaly observed in the two rugby shots was the strong core asymmetry, particularly for the high-energy shot. Evidently, the inner beams (23.5°, 30°) are impeded near the LEHs, and the responsible physical mechanism remains to be identified. Table I shows values for the simulated, time-integrated, imploded core image distortion for both rugby shots without use of a mix model (η_p=0; see below). According to mainline 2-D radiation-hydrodynamics (RH) simulations using the "high flux model" (HFM)[8], which is characterized by the generous use of an electron thermal flux limit of 0.15 and a detailed configuration accounting (DCA) atomic physics non-local-thermodynamic equilibrium (NLTE) model, the imploded cores are close to round or even mildly prolate in shape. The leading explanation for the large difference is that the inner beams are effectively stopped near the LEH from elevated Au wall motion near the LEHs, whether due to a less emissive (or hotter) wall than expected or from hydrodynamic mix of the Au with the confining helium gas. Scientists at CEA (France) have had recent success in simulating both rugby shots using a Busquet-type NLTE model [9] that provides the necessary enhancement in wall motion compared with the HFM. An alternative approach is to append a mix model to the HFM to achieve the requisite wall motion for the observed levels of core asymmetry.

3.1. Implementation of a fall-line mix model

To explain this large discrepancy in symmetry we invoke a physical effect that has been overlooked to date. The Au/He interface is considerably unstable to hydrodynamic perturbations, whether generated by laser imperfections such as speckle or initial hohlraum surface roughness. Figure 1a shows the interface Atwood number (*At*) versus time at the hohlraum equator, indicating high values (*At*>0.85) through the foot portion of the laser drive. Figure 1b shows the acceleration history of this interface with a strong and extended episode of deceleration (g~-5 μm/ns^2) from the laser-heated helium gas fill pushing back on the expanding gold wall after ~1ns and persisting through the foot. An early-time seed for Rayleigh-Taylor instability (RTI) could be through laser speckle on the Au/He interface during the laser picket at early time ~1 ns. Smoothing by spectral dispersion (SSD) is limited to one spatial dimension in hohlraum experiments, and speckle is expected to persist with a characteristic width: $\Delta_s = 2f\lambda$, where the f number of a NIF beam is ~20 and λ is the incident laser wavelength (0.351 μm). The classical RTI growth rate is $\sqrt{At \cdot kg}$, where $k = 2\pi / \Delta_s$ is the wavenumber of the speckle perturbation. For a conservative growth time of ~10 ns, the number of *e*-foldings is ~16, giving an amplification factor of ~10^6. Unless the "equivalent surface perturbation" [10] is highly sub-Angstrom, the perturbation growth from laser speckle is expected to quickly saturate and become nonlinear. In this case, we can invoke a self-similar Youngs' model for a fully

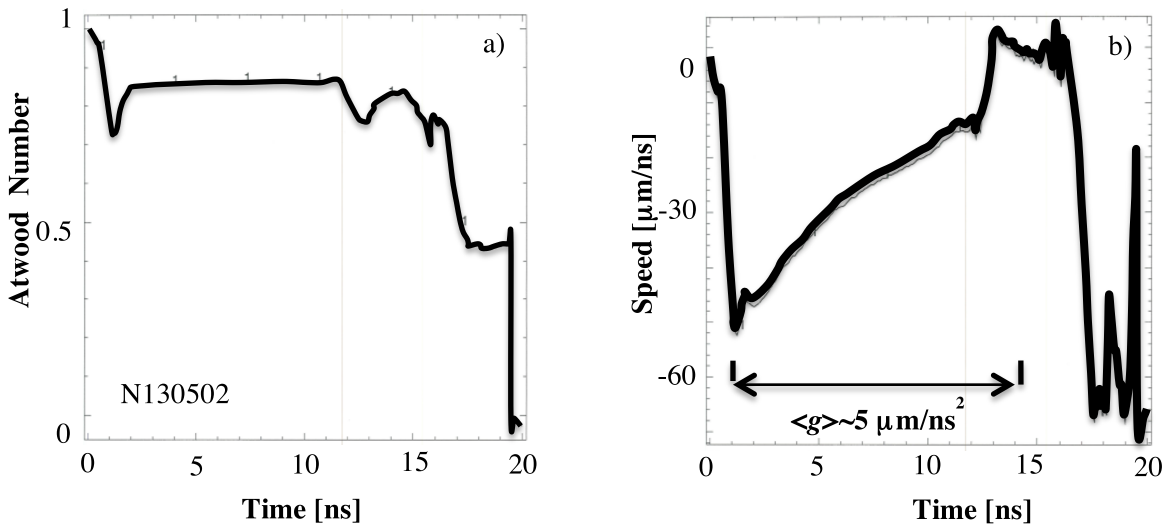

Fig. 1a-b: (a) Helium-Au interface Atwood number history for shot N130502, and (b) interface speed.

developed mix layer [11] with a characteristic loss of memory of initial conditions. The corresponding mix layer evolution scales as $\Delta_{b,s} = \alpha_{b,s} At \cdot gt^2$, where α_b=0.063 is the bubble coefficient [12] and $\alpha_s = \alpha_b[(1+At)/(1-At)]^{0.34}$ is the spike coefficient [13]. By 12 ns, the total mix width has grown to over 100 µm on the equator, representing a significant source of extra wall motion beyond what mainline HFM-based RH simulations predict.

The simplest and most physically appealing mix model to incorporate in mainline RH simulations is the fall-line mix model [14]. The fall-line model is a prescription for mixing interface material a prescribed ("penetration") fraction η_p of the distance from the "clean" interface to the fall line, or straight-line trajectory of material ejected away from the interface at the instant of peak interface speed. Its appeal is two-fold: (1) only a single free parameter (η_p) is required, and (2) the nonlinear quadratic dependence on time of the mix layer evolution follows naturally from construction of the mix width after deceleration onset. Figure 2a-b applies the model to the pair of rugby shots, showing

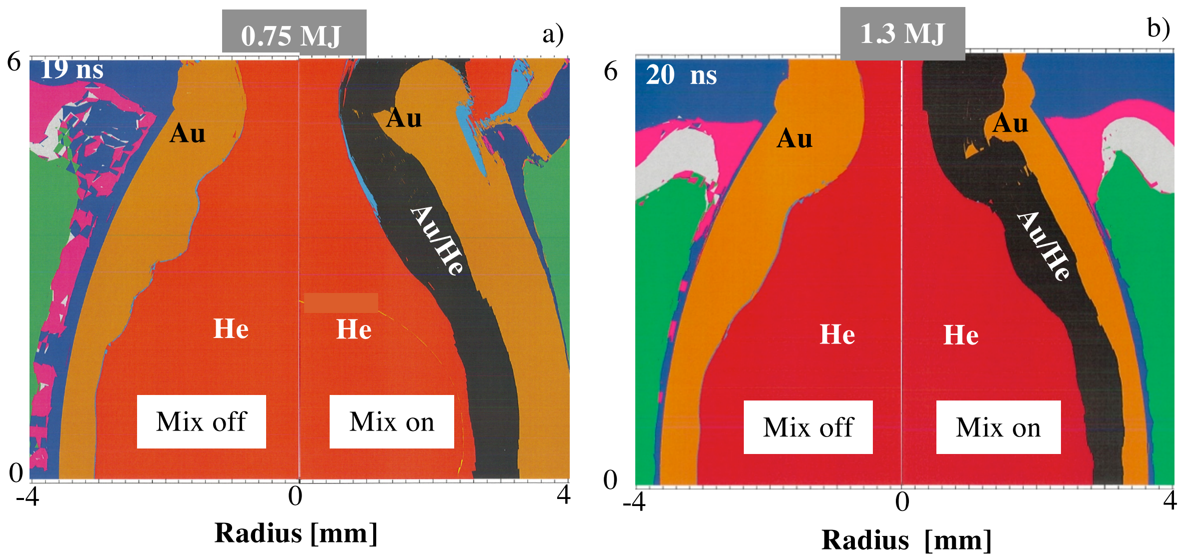

Fig. 2a-b: (a) Hohlraum materials for 0.75 MJ shot with and without mix at 19 ns; (b) 1.3 MJ at 20 ns.

that a penetration fraction of 100% provides an increased level of wall motion (~200 μm) at the LEH, which is in rough agreement with the above estimate for nonlinear mix and the observed core asymmetry (see Table I). A limit for η_p=100% is fixed by causality according to hydrodynamic constraints, but plasma kinetic effects could play a role in exceeding this limit. For example, a non-thermal population of energetic Au ions at ~10 T_i with an average ionization state of ~50 could significantly affect core symmetry if mixed uniformly with the He at only a few parts in 10^4, according to RH simulations.

3.2. Future

The rugby-hohlraum platform for a low-adiabat implosion was not intended to be a test bed for hohlraum mix, but the data may be consistent with such an outcome. These findings may have relevance for the dynamics of mainline cylinder hohlraums as well, where 3-D modeling of the outer cone Au bubble evolution underestimates the growth compared with the SXI data from "Viewfactor" hohlraums [15]. In addition, the (ion acoustic) perturbed ion number density is treated as a free parameter in RH simulations with large wavelength separation to match the observed core symmetry [16], allowing the possibility that a mix component could be present in cylinders - albeit at a reduced level compared with rugby hohlraums because of the (geometrically) less available volume for mix near the LEHs. The immediate plan is to reduce the potential influence of enhanced wall motion, whether due to mix or a less emissive NLTE physics model, by repointing of the outer beams, using a higher gas fill (but without incurring excessive hydro-coupling risk) in tandem with a higher foot (higher adiabat) pulse shape, adopting smaller phase plates, implementing shape changes near the LEHs, or low-*Z* liners.

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References

[1] Boehly T *et al.* 1997 *Opt. Commun.* **133** 495

[2] Philippe F *et al.* 2010 *Phys. Rev. Lett.* **104** 035004
Robey H *et al.* 2010 *Phys. Plasmas* **17** 056313

[3] Philippe F *et al.* 2013 *Phys. Rev. Lett.* (submitted)

[4] Amendt P *et al.* 2007 *Phys. Plasmas* **14** 056312

[5] Kline J L et al. 2013 Phys. Plasmas **20** 056314

[6] Kyrala G A *et al.* 2011 *Phys. Plasmas* **18** 056307

[7] Amendt P *et al.* 2008 *Phys. Plasmas* **15** 012702

[8] Rosen M D *et al.* 2011 *High Energy Density Physics* **7** 180

[9] Busquet M 1993 *Physics Fluids* **5** 4191

[10] Azechi H *et al.* 1997 *Phys. Plasmas* **4** 4079
Schmitt A *et al.* 2001 *Phys. Plasmas* **8** 2287

[11] Youngs D L 1984 *Physica D* **12** 32

[12] Dimonte G *et al.* 2005 *Phys. Plasmas* **12** 056301

[13] Dimonte G 2000 *Phys. Plasmas* **7** 2255

[14] Amendt P *et al.* 2002 Phys. Plasmas **9** 2221
Amendt P, Milovich J L, Perkins L J, and Robey H F 2010 *Nucl. Fusion* **50** 105006

[15] Schneider M B et al. "The ViewFactor Experiments at the National Ignition Facility", this Proceedings

[16] Town R P J *et al.* 2011 *Phys. Plasmas* **18** 056302